Characteristics of pressure and integral loads on prisms in boundary layer flows

Kyle Butler[a], Ahsan Kareem[a]
[a]*NatHaz Modeling Laboratory, University of Notre Dame, Notre Dame, IN, USA*

ABSTRACT: The spatial and temporal structure of random pressure fields, the nature of fluid-structure interactions and associated loads acting on finite height, surface mounted prisms are examined. Two prismatic cylinders exposed to boundary layer flows of varying turbulence intensity, simulating varying terrain conditions, are studied here. The following measured and derived features of the pressure field around these prisms, with a focus on aspect ratio and approach flow features, are discussed here: local pressure power spectra; pressure cross-correlation structure on windward, leeward and side faces; alongwind, acrosswind and torsional load spectra; influence of approach flow incidence on integral loads. The mechanisms responsible for the modifications of flow features, particularly the incident flow and aspect ratio, are critically examined. Results demonstrate a unique influence of the approach flow field characteristics that results in either enhancing or suppressing the development of coherent flow features, particularly at varying angles of attack.

KEYWORDS: bluff body aerodynamics; aspect ratio; pressure field; wind induced forces; turbulence; boundary layer.

1 INTRODUCTION

The study of fluid-structure interaction is of critical importance to wind engineering, and has been the subject of numerous investigations (e.g. Vickery 1966, Lee 1975, Hillier and Cherry 1981, Bearman and Morel 1983, Kareem and Cermak 1984, Kareem 1990, Surry and Djakovich 1995, Saathoff and Melbourne 1999). The fundamental studies, focusing on the nature of the resulting pressure fields on prismatic cylinders, have shown that changes in turbulence intensity impact the nature of shear layer separation, development and reattachment on the surfaces parallel to wind, concluding that increasing turbulence intensity serves to induce earlier reattachment of the flow while broadening and lowering peaks in the spectral description of pressure fluctuations. Some of these changes attributed to varying inflow conditions can be estimated as a result of the self-similar nature of the pressure field, when complete reattachment is promoted (Yeung 2005). The level of correlation within these pressure fields has shed insight into the scale of coherent structures formed as a result of varying aspect ratio and inflow conditions. Particularly for finite height prisms, the correlation structure has revealed the nature of the separation and reattachment regions, and the reduction in the correlation due to increasing turbulence conditions. In terms of the resulting forces, test measurements and computational simulations have revealed that acrosswind is the predominant loading in the prismatic structures, as noted in earlier studies.

Recent work (e.g., Lin et al. 2005) has highlighted various aspects in the windward integral loads on isolated prismatic models, utilizing force coefficients, correlation and spectral descriptions. Their experimental data indicate a critical aspect ratio at which the acrosswind force is significantly reduced as a result of a compromised shear layer. However, experimental variables, such as turbulence intensity, can affect the critical value and the transitional nature of these forces. Similar studies (e.g., Yu et al. 2006) have attempted to isolate the evolutionary

nature of the flow field in response to the changing aspect ratio, indicating other critical points. A time-frequency analysis of the drag and lift forces demonstrated intermittent behaviors and other evolutionary features that were not revealed in the power spectrum, which fails to capture localized effects in time.

This paper is an extension of an earlier presentation by Kareem (1990) in which the characteristics of wind generated pressure fields and their integral effects were examined in detail. This work re-examined the nature of wind generated pressure fields, examining local characteristics and global trends. Three primary variables were involved in this study: cross-sectional aspect ratio, inflow conditions and the angle of attack.

2 EXPERIMENTAL SETUP

An initial description of the experimental setup was presented in Kareem (1990). Measurements were obtained in a boundary layer wind tunnel facility at the University of Houston with a test section that was 60 ft. long and 10 ft. by 5 ft. in cross-section. Two typical boundary layers (referred to as BLI and BLII) were simulated for this study. The kinematics of the turbulent flow profiles associated with BLI and BLII are similar to the flow of open country and urban environments, respectively.

The prisms utilized in this study had width to breadth ratios, aspect ratio of the plan dimensions, of 1:1.5 (aspect ratio 1.5) and 1.5:1 (aspect ratio 0.67), measuring 5 in. on the narrow face, 7.5 in. on the broad face and had a height of 20 in. Each model was instrumented with pressure ports at five levels, and at varying locations on the side faces which were connected to a Setra pressure transducer system. The system was dynamically calibrated to determine amplitude and phase distortion, while each channel of the measured data was digitally corrected to recover the undistorted signal.

3 RESULTS AND DISCUSSION

This experiment involved three variable parameters: the aspect ratio of the model, the turbulence intensity of the oncoming wind speed profile and, for some results, the angle of attack of the inflow. Analysis of the mean pressure distribution and RMS pressure distribution around both prisms showed that recovery of pressures is promoted by higher turbulence intensity, especially when the aspect ratio is greater than one. This indicates that the afterbody length must be sufficiently larger than the recirculation zone for the recovery of pressures to be promoted, when the intensity of turbulence is held as a constant. The zone of recalculating flow is influenced by the length of the side face, thus linking the development of the separated shear layer and the subsequent shedding of vortices to the aspect ratio. Additionally, the increase in turbulence intensity had the effect of modifying the features of the separated shear layer on the side face, as a result of increased mixing between the free stream and the separated shear layer. These trends were identified both through the investigation of local spectra and through their spatio-temporal chordwise correlation structure. In most cases, the general trend of the flow behavior agreed well with previous experiments. Analysis of the integral alongwind, acrosswind and torsional loading spectra, at varying angles of attack, revealed a critical angle of approximately 15º wherein the dominant frequency content begins to shift as a result of changes in the shear layer and prism edge interaction.

3.1 *Local pressure power spectra*

Detailed examination of the power spectra of local pressure measurements on the alongwind face, taken at the mid-height level to reduce impacts from end effects (e.g. Kareem and Cermak, 1984; Wang et al. 2005), revealed behaviors that described the shear layer separation, coherent structure development, and subsequent flow reattachment in tandem with changes in the inflow conditions. In brief, there is a redistribution of frequency content in both aspect ratio cases, observed from the leading to the trailing edge. Figures 1 and 2 show the spectral evolution of local pressures in the alongwind direction on the side face for both boundary layer conditions.

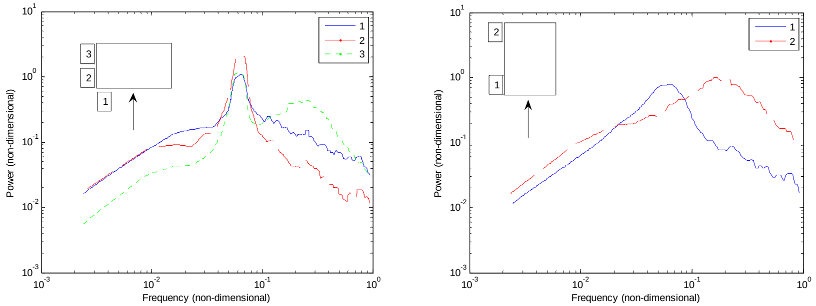


Figure 1: Local spectra of pressure fluctuations in BLI for aspect ratios (a) 0.67 and (b) 1.5

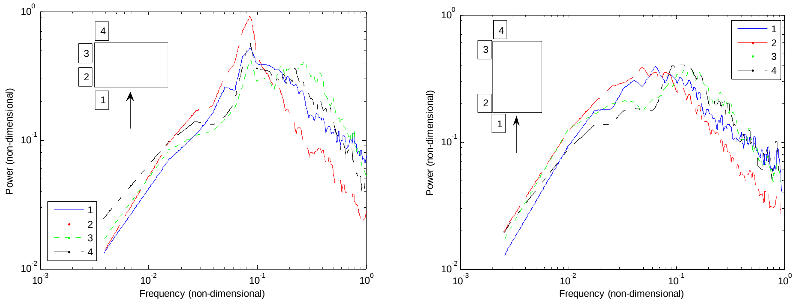


Figure 2: Local spectra of pressure fluctuations in BLII for aspect ratios (a) 0.67 and (b) 1.5

The development of pressures on prismatic models is characterized by spaito-temporal fluctuations with distinct frequency contents, with chordwise flow evolution being primarily a function of aspect ratio. Identifying the cause of multiple frequency peaks in the power spectra could help in either promoting or suppressing their existence with subsequent shape or surface modification, which are increasingly being used in practice. In both aspect ratio cases presented, the spectra show a dominant peak near the non-dimensional value of 0.075 at taps located around the leading edge. As the flow evolves, pressures on the trailing edge of the short aspect ratio model retain the leading edge frequency content, while the pressures on the trailing edge of the larger aspect ratio model exhibit metastasizing of energy content to different frequency components. Since the presence of a primary peak is sustained at taps in the locale of the trailing edge for the smaller aspect ratio model, it suggests that a less complete reattachment of the flow is occurring when compared to the larger aspect ratio model, where there is a complete shift to higher frequency content, indicating a change in the flow structure. It is also noted that due to feedback, pressure tap 1 on the windward face also reflects the features of pressure fluctuations at tap 2 on the side face alluded to earlier in (Kareem 1986). Upon examination of the pressure spectra for the BLI inflow, it is noted that the primary frequency content shifts as the points of observation move away from the leading edge. In both cases, the initial peak is near a non-dimensional value of 0.075 (though it is slightly less for the larger aspect ratio model). As the flow evolves, the trailing edge pressure spectra shift to higher frequency content for both aspect ratios studied, as a result of the influence of afterbody length.

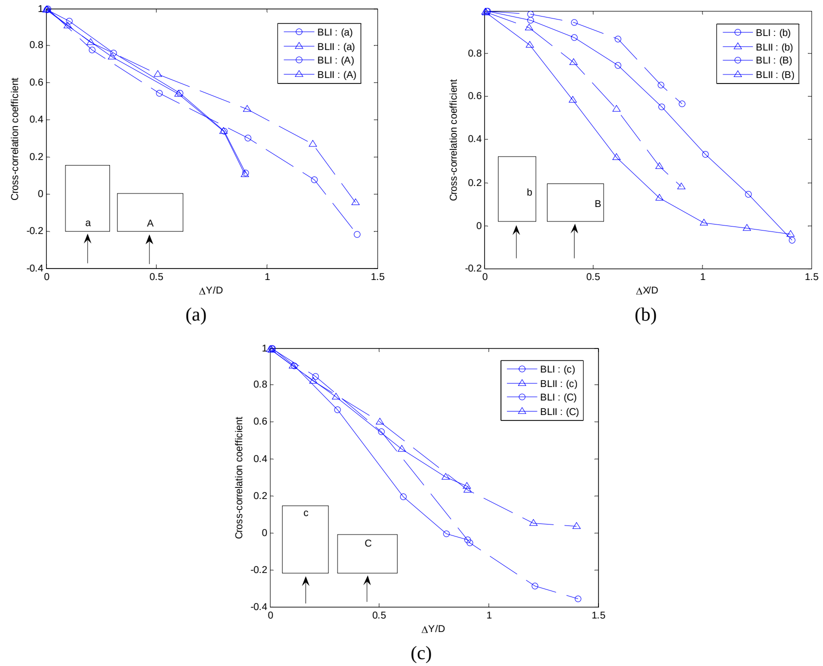


Figure 3: Chordwise cross-correlation structure on the (a) windward, (b) side and (c) leeward surfaces.

3.2 *Pressure cross-correlation structure on prism surfaces*

The correlation structure of the enveloping flow field around prism surfaces varies with both the incident turbulence and the aspect ratio. General observations about the correlation structure were presented in Kareem (1997). Figure 3 shows the chordwise cross-correlation coefficients, at mid-height, for the windward, side and leeward faces. Prior research has demonstrated that the level of incident turbulence impacts the flow behavior on the side face, particularly influencing the development, circulation and reattachment of separated shear layers from the leading edge, and is demonstrated in Figure 3b where the reduction in value for the BLII condition near the downstream edge indicates earlier flow reattachment. On the windward and leeward surfaces for both aspect ratios, the correlation coefficients for the turbulent flow case were higher than those of the smooth flow condition. Interestingly, the correlation structure on the windward face for both models contains a fair amount of detail regarding the impact of aspect ratio, as opposed to the inflow condition. The larger aspect ratio shows that the chordwise correlation structure is identical for both boundary layer conditions. However, the smaller aspect ratio model shows a discrepancy between the chordwise correlation profiles of both inflow conditions, where the more turbulent condition shows higher values than the relatively quiescent flow. It is hypothesized that flow reattachment on the larger aspect ratio through feedback stabilizes the flow at the leading edge, producing similar correlation values regardless of incident flow. Conversely, the smaller aspect ratio has no stable flow field development, impacting the flow at the leading edge as shown by the difference in correlations.

The rear surface chordwise correlations show a significant difference between the two approach flow conditions and that it is affected by the aspect ratio, with BLII having a much higher correlation than BLI. The smaller aspect ratio indicates that there is a reversed flow region, as a result of the separated shear layer, though this only occurs for BLI. The turbulent boundary layer potentially entrains much of the surrounding flow, leading to modestly higher correlations on the leeward surface.

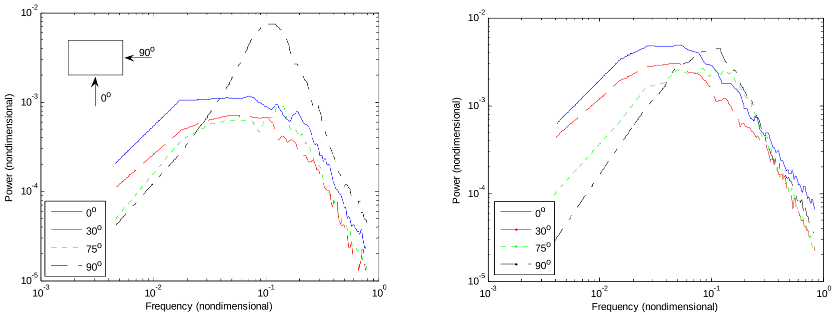


Figure 4: Alongwind loading spectra of the prismatic model at various angles of attack and boundary layer condition (a) BLI and (b) BLII.

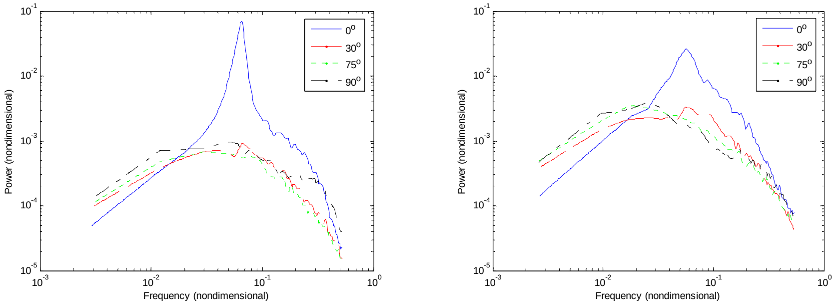


Figure 5: Acrosswind loading spectra of the prismatic model at various angles of attack and boundary layer condition (a) BLI and (b) BLII.

3.3 *Alongwind and acrosswind load spectra*

The alongwind and acrosswind loading spectra of the two prisms in two inflow conditions were acquired through the use of a high frequency base balance and the pneumatic averaging of pressures to resolve mode generalized spectra from pressure measurements. For brevity, this data is shown in Figures 4 and 5, respectively, at 0º and 90º incidence. The peak in the loading for the smaller aspect ratio is primarily dominant in the acrosswind direction, while in the case of the larger aspect ratio the peak is less pronounced and is more diffused over a wider bandwidth. Apparently, added turbulence in the dynamics of integral loads plays a role akin to damping in a linear dynamic system, which is portrayed by their spectral descriptions.

3.4 *Torsional load spectra*

The torsional loading spectra in this study were acquired by weighted summation of pressures at each level (Kareem 1990). Recent work (Liang et. al. 2004) continues to investigate the nature of torsional loading on finite prismatic models because of its complex nature. It particularly highlights the dependent nature between the cross-sectional aspect ratio and the prominence of peaks within the torsional spectra. Dual peaks were observed with larger aspect ratios as a result of both vortex shedding and reattachment, while smaller aspect ratios were governed by turbulence and vortex shedding on the side faces. The experimental results, shown in Figure 6, demonstrate the effect of increasing turbulence intensity has on not only muting significant peaks in the spectra, but also shifting the energy content to relatively lower frequencies. In both aspect ratios, the primary range of frequency content is below 0.1. However, the smaller aspect ratio retains only the content centered at the lower peak, whereas the larger aspect ratio retains content at two spectral peaks. This indicates that aspect ratio is a critical factor in the development of dominant frequency components. The exact mechanism regarding the torsional motion of rectangular prisms is thought to be due to anti-symmetric pressure field introduced by vortex shedding and the pressure field resulting from reattachment on the side faces, where the former dominates in the case of small aspect ratios. A similar observation was made in Isyumov and Poole, 1983 and Kareem 1990.

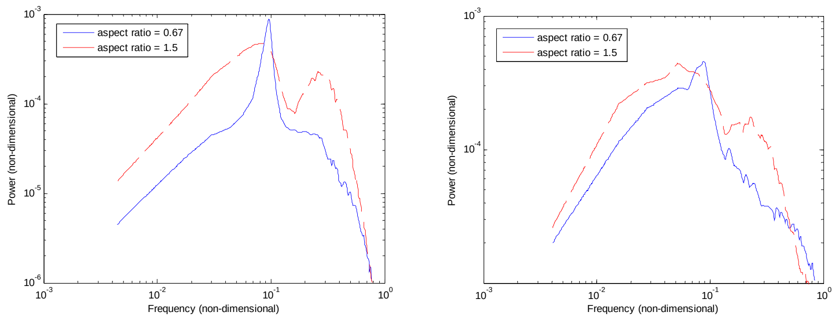


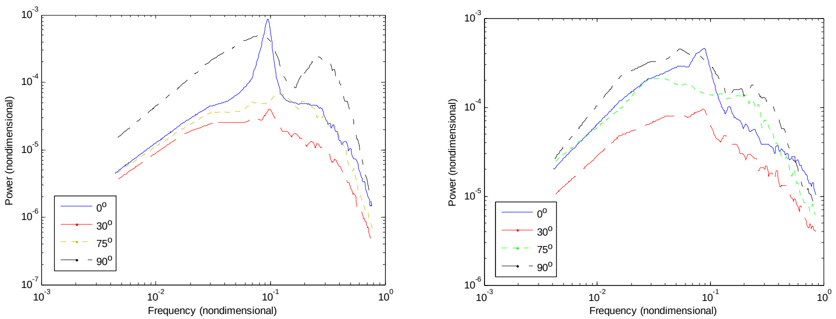
Figure 6: Torsional loading spectra for the prisms within (a) BLI and (b) BLII.

3.5 *Characteristics due to changing incidence angle*

Along with the aspect ratio and incident turbulence, information on the behavior of the prismatic models with changing flow incidence was also examined. In particular, the alongwind, acrosswind and torsional spectra were examined using both pneumatic averaging and high frequency base balance. Each experiment was conducted establishing the 0º flow incidence on the long face. The alongwind and acrosswind loading spectra of the prismatic models with varying incident flow angle are shown in Figures 4 and 5, respectively. Both aspect ratio cases show focused energy content in the spectra of acrosswind loading, and both cases show broadening spectral content as the level of turbulence intensity is increased. Dramatic shifts in energy content occur when the flow is within 30º of the direction generating the peak acrosswind load.

The torsional loading of the prismatic model as taken from the high frequency base balance, shown in Figure 7, is affected by all three variables presented. At the initial orientation of the flow, the power spectra of the torsional loading showed a distinct peak at one frequency. Varying the inflow turbulence significantly reduced this peak, distributing more of the energy to neighboring frequencies, but not eliminating the primary frequency component. Rotating the model through 90º revealed the changing nature of the fluid-structure interaction. In both boundary layer flows, when the model is oriented beyond 30º to the original flow angle the initial peak is significantly muted, but not eliminated. It is not until the model is rotated beyond 75º that the primary peak is removed in the spectral description reflecting the redistribution of energy within the new flow regime. This behavior occurs regardless of the oncoming flow condition. When the incident flow is oriented to the large aspect ratio prism (90º), two distinct peaks appear. The nature of the torsional loading with respect to aspect ratio and flow incidence angle shows that for both aspect ratios, peaked spectral content for torsional loading occurs within 30º of the either plan principle axis of the prisms, while muted spectral content occurs in the intermediate angle orientations (which are not presented for brevity).

Comparing the alongwind, acrosswind and torsional frequency description of the two models in total reveals further behavior. For the smaller aspect ratio, there is no dominant peak in the alongwind direction, indicating that the acrosswind loading governs the torsional behavior. For the larger aspect ratio, there is different energy content in both the alongwind and acrosswind directions, giving rise to the dual peaked nature of the resulting torsional spectra. Based on this comparison, it would seem that the acrosswind loading mechanism plays a major role in the loading pattern of these prisms regardless of the wind orientation.



(a) (b)

Figure 7: Torsional loading spectra of the prismatic model at various angles of attack and boundary layer condition (a) BLI and (b) BLII.

4 CONCLUSION

The experimental results presented continue, and expand upon, the examination of flows around prismatic structures and the nature of the resulting forces. Results show that both turbulence intensity and aspect ratio contribute to the nature and behavior of the separated shear layer, subsequent vortex development, and recovery of pressures. As a result, various trends within the frequency content of the pressure and integral load spectra were observed. Local spectra of pressure fluctuations demonstrate the development of salient features of flow structures as they evolve over the side faces, characterized by a shifting of the primary frequency content within the spectra. The alongwind, acrosswind and torsional spectral characteristics are defined by the aspect ratio, turbulence intensity and orientation to flow. For short aspect ratio, vortex shedding plays a primary role, whereas in the larger aspect ratio case, both vortex shedding and the reattached flow field drive the development of loading patterns. The overall trends related to the changes in turbulence intensity and aspect ratio agree well with the existing body of work.

5 ACKOWLEDGEMENTS

The partial support of NSF Grant CMS 03-24331 for this study is greatly appreciated.

6 REFERENCES

1 B. Vickery, Fluctuating lift and drag on a long cylinder of square cross-section in a smooth and in a turbulent stream, Journal of Fluid Mechanics 25 (1966) 481-484.
2 B. E. Lee, The effect of turbulence on the surface pressure field of a square prism, Journal of Fluid Mechanics 69 (1975) 263-282.
3 R. Hillier, N.J. Cherry, The effects of stream turbulence on separation bubbles, J. Wind Eng. Ind. Aerodyn. 8 (1981) 49-58.
4 P.W. Bearman, T. Morel, Effect of free stream turbulence on the flow around bluff bodies, Progress in Aerospace Sciences, 20 (1983) 97-123.
5 A. Kareem, J.E. Cermak, Pressure fluctuations on a square building model in boundary-layer flows, J. Wind Eng. Ind. Aerodyn. 16 (1984) 17-41.
6 A. Kareem, Measurements of pressure and force fields on building models in simulated atmospheric flows, J. Wind Eng. Ind. Aerodyn. 36 (1990) 589-599.
7 D. Surry, D. Djakovich, Fluctuating pressures on models of tall buildings, J. Wind Eng. Ind. Aerodyn. 58 (1995) 81-112.
8 P. Saathoff, W.H. Melbourne, Effects of freestream turbulence on streamwise pressure measured on a square-section cylinder, J. Wind Eng. Ind. Aerodyn. 79 (1999) 61-78.
9 W.W.H. Yeung, Similarities of pressure induced by separation bubble in grid-generated turbulent flow, J. Wind Engl Ind. Aerodyn. 39 (2005) 293-309.
10 A. Kareem, Correlation structure of random pressure fields, J. Wind Eng. Ind. Aerodyn. 69-71 (1997) 507-516.
11 N. Lin, C. Letchford, Y. Tamura, B. Liang, O. Nakamura, Characteristics of wind forces acting on tall buildings, J. Wind Eng. Ind. Aerodyn. 93 (2005) 217-242.
12 D. Yu, A. Kareem, K. Butler, J. Glimm, J. Sun, Numerical investigation of the influence of aspect ratio on flows around bluff bodies, CWE2006, Yokohama, Japan (2006).
13 H.F. Wang, Y. Zhou, C.K. Chan, Flow around a finite length square prism, Fourth European & African Conference on Wind Engineering, Prague, July, 2005, paper #314.
14 A. Kareem, Synthesis of fluctuating alongwind loads on buildings, Journal of Engineering Mechanics, ASCE, 112 (1986) 121-125.
15 S. Liang, Q.S. Li, S. Liu, L. Zhang, M. Gu, Torsional dynamic wind loads on rectangular tall buildings, J. Wind. Eng. Ind. Aerodyn. 26 (2004) 129-137.
16 N. Isyumov, M. Poole, Wind induced torque on square and rectangular building shapes, J. Wind Eng. Ind. Aerodyn. 13 (1983) 183-196.